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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 424

PRELIMINARY PHOTOMICROGRAPHIC STUDIES OF FUEL SPRAYS

By Dana W. Lee and Robert O. Spencer  
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### PRELIMINARY PHOTOMICROGRAPHIC STUDIES OF FUEL SPRAYS

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#### SUMMARY

Photomicrographs were taken of fuel sprays injected into air at various densities for the purpose of studying the spray structure and the stages in the atomization of the fuel. The photomicrographs were taken at magnifying powers of 2.5, 3.25, and 10, using a spark discharge of very short duration for illumination. The results indicate that the theory advanced by Dr. R. A. Castleman, jr., on the atomization of fuel in carburetors may also be applied to the atomization of fuel sprays of the solid-injection type. The fuel leaves the nozzle as a solid column, is ruffled and then torn into small, irregular ligaments by the action of the air. These ligaments are then quickly broken up into drops by the surface tension of the fuel. The photomicrographs also show that the dispersion of a fuel spray at a given distance from the nozzle increases with an increase in the jet velocity or an increase in the air density. The first portions of fuel sprays injected from an automatic injection valve into air at atmospheric density have a much greater dispersion than the later portions, but this difference decreases rapidly as the air density is increased.

#### INTRODUCTION

In the course of the general research on fuel sprays for compression-ignition and spark-ignition engines of the solid-injection type, much information has been gathered about the external form of the sprays, their penetration and dispersion, and about the atomization and distribution of the fuel within the sprays. From various phenomena observed, inferences have been drawn concerning the internal structure of the sprays and the nature of the atomization process. However, very little direct information has been available concerning this process.

At the laboratory of the National Advisory Committee for Aeronautics, a large number of photomicrographs have recently been made of fuel sprays from a variety of nozzles used in fuel-injection work. They reveal details of spray structure which had heretofore been unobserved, and the true nature of which has been largely a matter of conjecture. The purpose of this note is to present a few of these photomicrographs accompanied by a brief discussion of the results obtained. The work is being continued, and a more complete account of the results will be published later.

#### APPARATUS AND METHODS

A microscope with camera attachment was used to take photomicrographs at a magnifying power of 10; camera lenses mounted in the end of a box about 2 feet long gave satisfactory photographs at magnifications of 2.5 and 3.25.

In each case the illumination was furnished by a spark discharge obtained with the electrical circuit described in reference 1. The spark gap was placed directly behind the sprays so that the photomicrographs are silhouettes.

The nozzles were used as part of an automatic injection valve and also as open nozzles. The injection valve was operated by the common-rail fuel-injection system of the N.A.C.A. spray photography apparatus. Synchronization of the spark and the spray was accomplished by a rotary disk switch on the same shaft with the cams that control the injection. The spark could be made to occur at any desired stage in the development of the spray by changing the phasing of the disk switch with respect to the camshaft. The sprays from the automatic injection valve were injected into a glass-walled chamber, in which the air density could be maintained above or below atmospheric. The sprays from the open nozzles were continuous, and were always injected into air at atmospheric density, the fuel being supplied under pressure from a reservoir arranged to maintain a constant pressure for several seconds. In this case the timing of the spark was manually controlled. The open nozzles were used with injection pressures up to 1,000 pounds per square inch, because the operation of the automatic injection valve was erratic at this and lower pressures.

## RESULTS AND DISCUSSION

The fact that the sprays were photographed as silhouettes should be kept in mind while studying the photomicrographs, because the core of the spray is the only part dense enough to register on the films. Most of the minute drops in the envelope of the spray surrounding the core could not be photographed.

It was found that the fundamental processes involved in the spray formation could be better observed in photomicrographs of sprays in air at atmospheric density than in those made at higher air densities. Fine details of sprays in dense air were so obscured by the cloud of mist surrounding the core that clear photographs could not be obtained. A better interpretation may be given to such photomicrographs after studying those made at air densities of one atmosphere or less.

The results obtained at atmospheric air density are directly applicable to the case of fuel injection during the intake stroke in spark-ignition engines.

## Sprays at Low Injection Pressures

The photomicrographs taken at injection pressures below 1,000 pounds per square inch are of special interest because of the clearness of detail obtainable and the fact that at these low pressures the disintegration of the fuel column is slower and the various stages are more distinctly separated.

The photomicrographs presented in this report show that the behavior of fuel sprays follows the process outlined by Dr. R. A. Castleman, jr., of the Bureau of Standards. He says in reference 2, concerning atomization by carburetion, "The actual process of atomization seems rather simple. A portion of the large mass is caught up (say, at a point where its surface is ruffled) by the air stream and, being anchored at the other end, is drawn out into a fine ligament. This ligament is quickly cut off by the rapid growth of a dent in its surface, and the detached mass, being quite small, is swiftly drawn up into a spherical drop." He compares "solid" injection of fuel to air-stream atomization, and concludes that the atomization

processes are similar, the formation of ligaments being controlled by the relative velocity between the air and the fuel in each case.

The breakdown of a low-velocity liquid column into drops, which is similar to the breakdown of a ligament as described by Castleman, is illustrated by Figure 1, which shows a stream of fuel injected from a 0.020-inch orifice at a very low pressure and consequently a very low velocity.

The photomicrographs of Figure 2 furnish many illustrations of the formation of ligaments and their breakdown into drops. The appearance of a constriction in the ligament just prior to breaking off is noticeable in a great many of the photomicrographs that have been taken. Many details observable on the original negatives, of which about 2,000 have been made, are lost in the process of reproduction. The similarity between the photomicrographs of Figure 2 and the photographs made by Scheubel of air-stream atomization in a model carburetor (reference 3) is very striking.

Figure 3 shows six stages in the development of a fuel spray injected at a low pressure into the atmosphere. Notice the ruffling of the fuel column near the nozzle, which grows in magnitude as the distance from the nozzle is increased. At still greater distances ligaments are formed which then collapse to form drops.

#### Effect of Injection Pressure

Figure 4 shows photomicrographs, taken 5 inches from the nozzle, of sprays injected into the atmosphere at various injection pressures. They show that the disruption of the fuel jet and the dispersion of the fuel particles increased as the injection pressure increased. At pressures above those shown, the dispersion is still greater, but the cloud of fine drops in the envelope caused the photograph to be blurred and unsuitable for reproduction. In the original negatives the formation of small ligaments is very noticeable even at injection pressures of 1,000 pounds per square inch and higher.

### Influence of Air Density

As has been mentioned before, all photomicrographs taken at densities other than atmospheric show sprays from an automatic injection valve. As shown in Figure 5, the first part of a spray from such a valve is more widely dispersed than the later portions. Photomicrographs of sprays injected into air having different densities showed that this difference in dispersion decreased rapidly as the air density was increased. As the injection progressed the dispersion became similar to that of continuous sprays, and photomicrographs made at the later stages are used in some of the following figures.

The influence of air density on the dispersion of fully developed sprays is shown by the photomicrographs in Figure 6. They show that the disruption of the fuel jet and the dispersion of the fuel particles increase with air density.

When different nozzles of like design were used to produce sprays in the evacuated chamber, it was found that the spray dispersion varied greatly. In some cases the sprays were nearly as well dispersed as when injected into the atmosphere, but in other cases the dispersion was very slight, even at high injection pressures. The differences are thought to be due to irregularities in the nozzles. In one case a nozzle that gave a well-dispersed spray was found to have a slight irregularity. After it was polished, the spray dispersion was less. As the air density was increased, the difference in the dispersion of sprays from different nozzles decreased, becoming very slight at the higher values used.

### Effect of Distance from the Nozzle

The photomicrographs of Figure 7 show how the appearance of a high-velocity spray changes as it travels away from the nozzle. The same stages were more distinct with a low-velocity spray. (Fig. 3.)

### Agreement with Experiments on Spray Atomization

Experiments have been performed at this laboratory (reference 4) in which the final sizes attained by the fuel particles in sprays were determined. The results showed that the drop sizes decreased with increasing jet velocity, but that changing the density of the air into which they were injected had no effect. Experiments by Sass (reference 5) showed the same results for different velocities, but indicated that the drop sizes decreased with increasing air density. The photomicrographs of Figures 6 and 7 show that, at a given distance from the nozzle, an increase in the air density causes a very decided increase in the dispersion, and probably a decrease in the mean drop size. Substantially the same results may be obtained by keeping the air density constant and increasing the distance from the nozzle. We may conclude that the atomizing process continues as long as the jet velocity is high enough to cause large particles to be torn apart to form smaller ones. In very dense air, the process is quickly carried to the limits obtainable with the jet velocity used; in air at low densities the jet loses its velocity more slowly and travels farther, but the final effect is the same. With the apparatus used by Sass the spray was caught after it had traveled about 8 inches, and it may be that the atomizing process was incomplete at that distance, especially at the lower air densities.

### CONCLUSIONS

The studies thus far made of the photomicrographs of fuel sprays indicate:

That the theory of air-stream atomization, advanced by Dr. R. A. Castleman, jr., appears to be directly applicable to the atomization of fuel sprays of the solid-injection type.

That at a given distance from the orifice, the disruption of the jet and the dispersion of the fuel increase with an increase in the jet velocity or an increase in the air density.

That at a given value of jet velocity and air density, the disruption of the jet and the dispersion of the fuel

increase with distance from the nozzle until the relative velocity between the fuel and the air becomes so low that the air no longer tears the fuel apart.

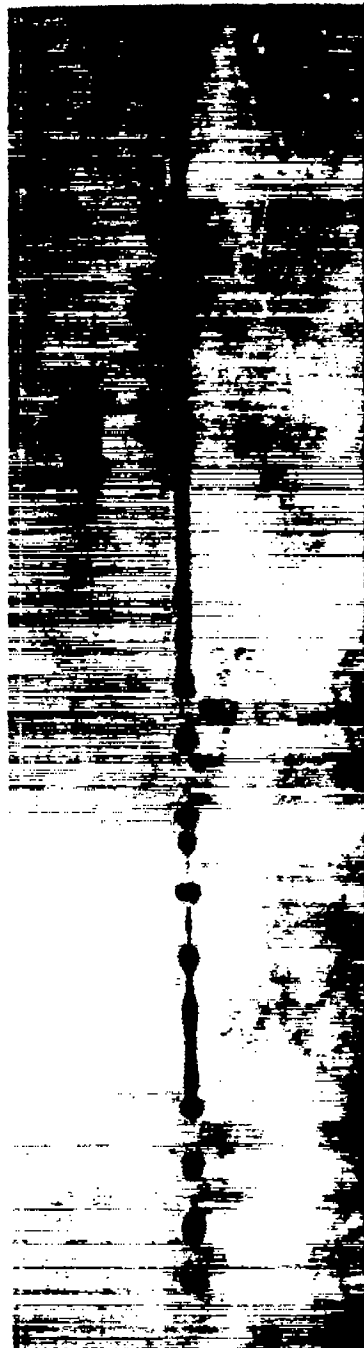
That at atmospheric and subatmospheric air densities, there may be wide differences in the dispersion of sprays from different nozzles of the same geometric design because of slight irregularities in the nozzles, and also between the early and later parts of sprays from nozzles used with automatic injection valves. At air densities corresponding to those in compression-ignition engines at the time of fuel injection the differences are slight.

Langley Memorial Aeronautical Laboratory,  
National Advisory Committee for Aeronautics,  
Langley Field, Va., June 13, 1932.

#### REFERENCES

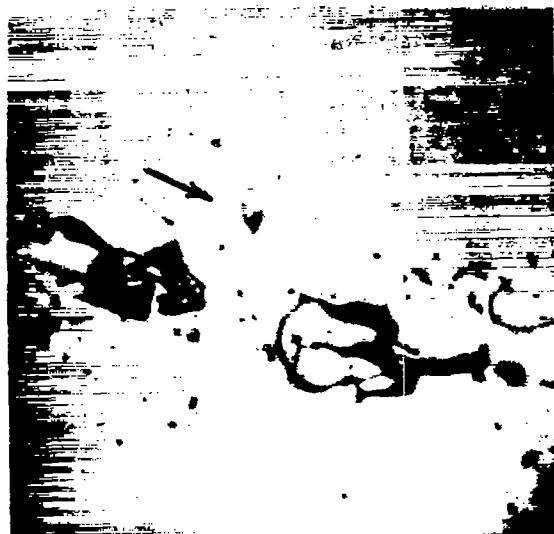
1. Lee, Dana W.: Experiments on the Distribution of Fuel in Fuel Sprays. T.N. No. 410, N.A.C.A., 1932.
2. Castleman, R. A., jr.: Mechanism of the Atomization of Liquids. Research Paper No. 281, Bureau of Standards Journal of Research, March, 1931.
3. Scheubel, F. N.: On Atomization in Carburetors. T.M. No. 644, N.A.C.A., 1931.
4. Lee, Dana W.: The Effect of Nozzle Design and Operating Conditions on the Atomization and Distribution of Fuel Sprays. T.R. No. 425, N.A.C.A., 1932.
5. Sass, F.: Kompressorlose Dieselmachines, Julius Springer (Berlin), 1929.





Injection pressure, 10 pounds per square inch  
Discharge orifice diameter, 0.020 inch  
Air density, 1 atmosphere

Fig. 1 Photomicrograph showing the breakdown of a  
fuel column into drops, X 3.25



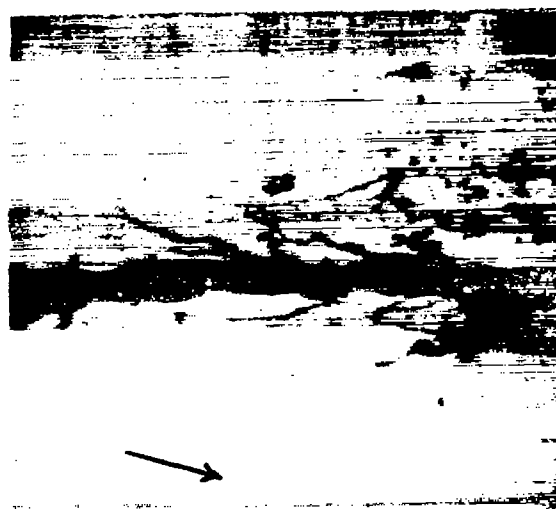
Injection pressure, 250 lb./sq.in.  
Orifice diameter, 0.014 inch  
Distance from nozzle, 5 inches



Injection pressure, 550 lb./sq.in.  
Orifice diameter, 0.020 inch  
Distance from nozzle, 5 inches

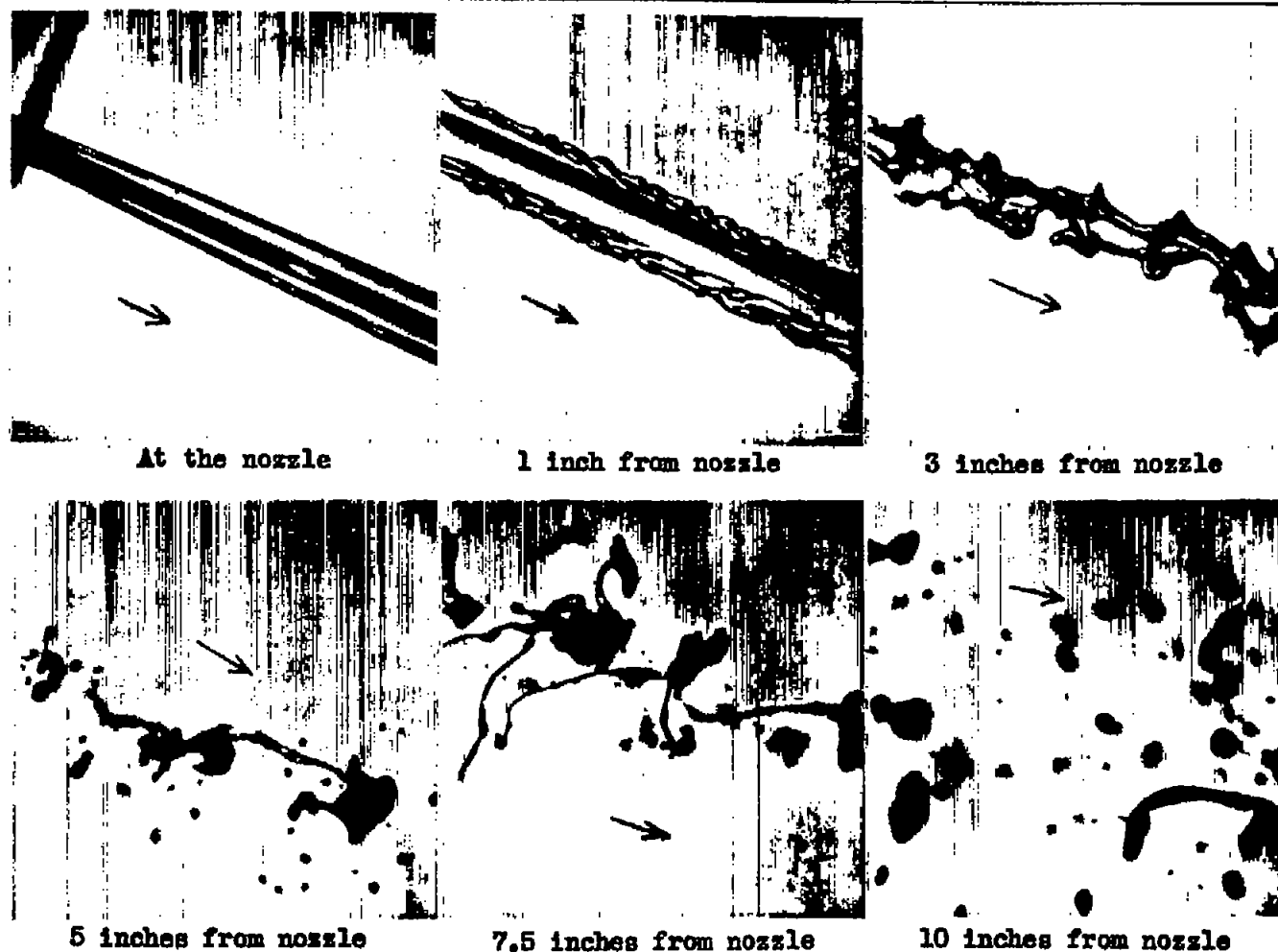


Injection pressure, 120 lb./sq.in.  
Orifice diameter, 0.020 inch  
Distance from nozzle, 7.5 inches



Injection pressure, 700 lb./sq.in.  
Orifice diameter, 0.020 inch  
Distance from nozzle, 1.5 inches

Fig. 2 Photomicrographs of fuel sprays showing the formation and breakdown of ligaments, X 10. All sprays continuous, injected into air at atmospheric density.

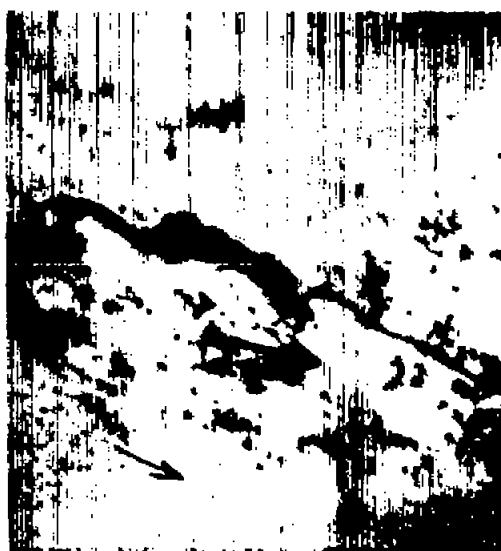


Injection pressure, 100 pounds per square inch  
 Air density, 1 atmosphere  
 Diameter of discharge orifice, 0.020 inch

Fig. 3 Photomicrographs showing the various stages in the breakdown of a low-velocity fuel jet, X 10



Injection pressure,  
200 pounds per square inch



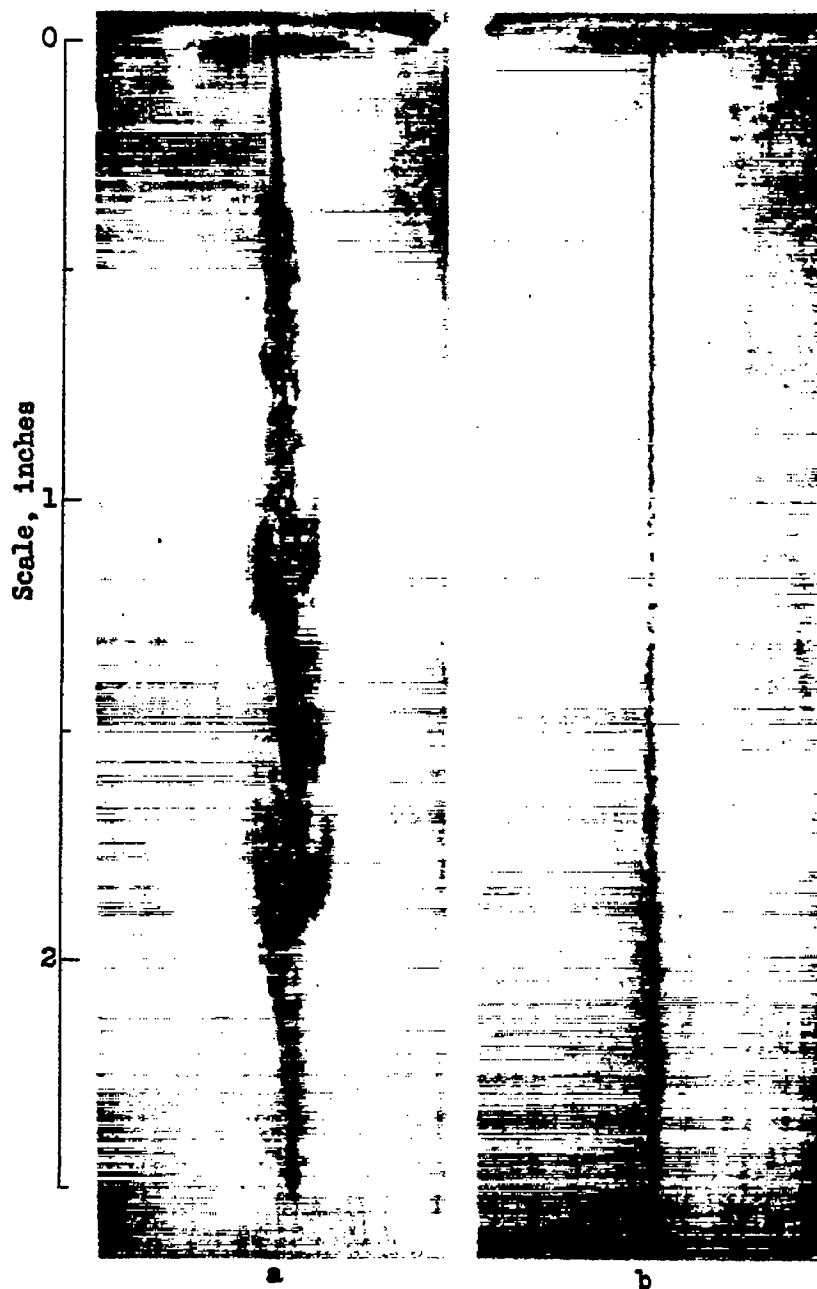
Injection pressure,  
500 pounds per square inch



Injection pressure,  
1000 pounds per square inch

Distance from nozzle, 5 inches  
Discharge orifice diameter, 0.020 inch  
Air density, 1 atmosphere

Fig. 4 Photomicrographs showing the effect of injection pressure on the atomization process, X 10



Injection pressure, 1500 pounds per square inch  
 Air density, 1 atmosphere  
 Discharge orifice diameter, 0.008 inch

Fig. 5 Silhouette photographs of fuel sprays from an automatic injection valve, X 2.5  
 (a) Start of spray  
 (b) 0.002 second after start of spray

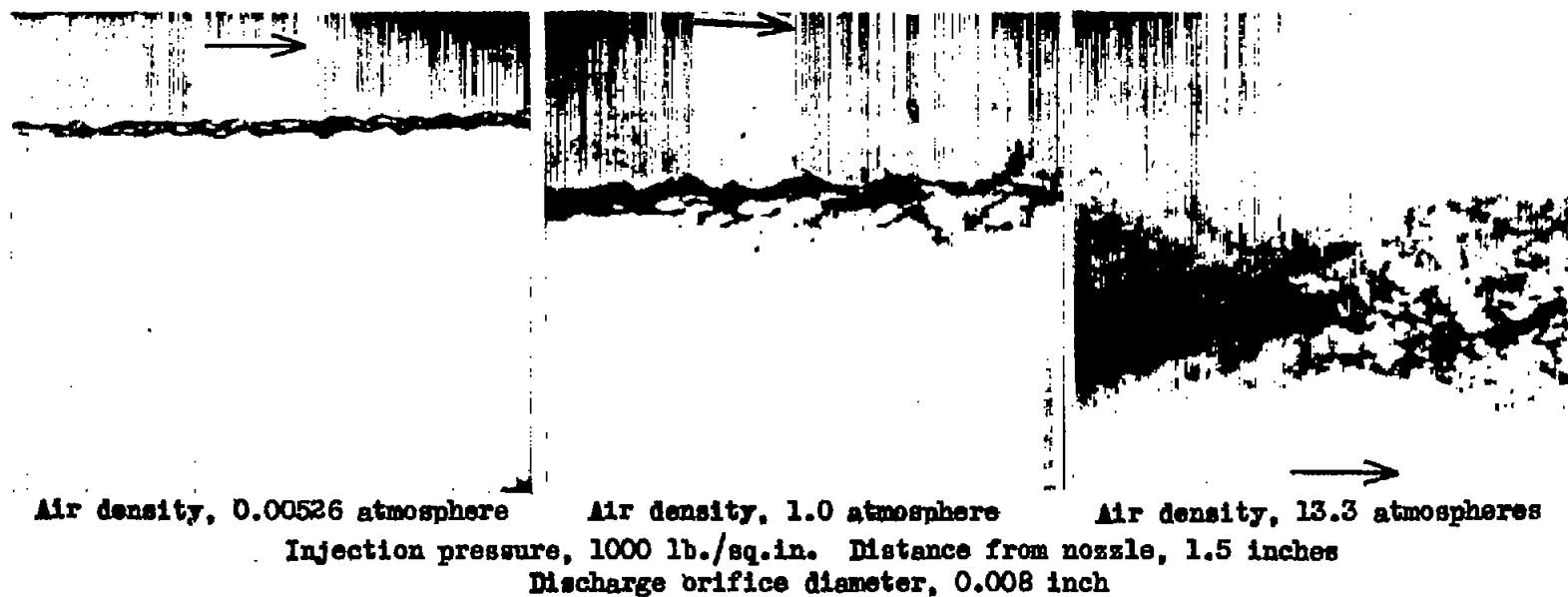


Fig. 6 Photomicrographs showing the effect of the density of the air into which the fuel is sprayed on the atomization process, X 10

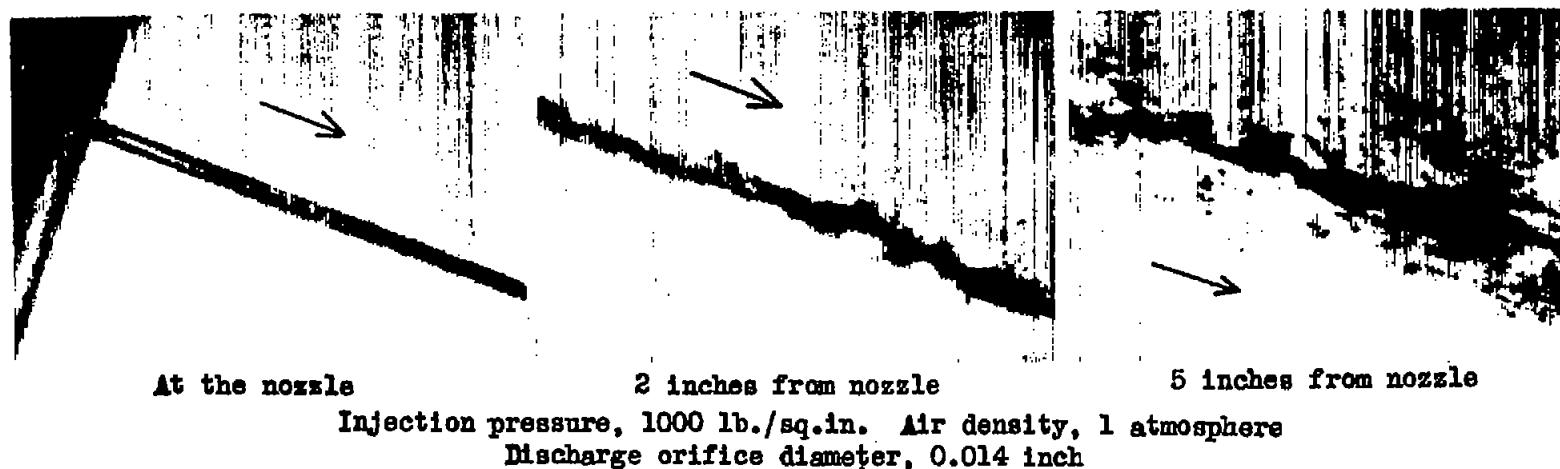


Fig. 7 Photomicrographs showing the atomization process at different distances from the nozzle, X 10